

Claims

1. A process for making hydrogen peroxide, comprising:

flowing a process feed stream and a staged addition feed stream in contact with each other in a process microchannel to form a reactant mixture comprising O<sub>2</sub> and H<sub>2</sub>, and contacting a catalyst with the reactant mixture in the process microchannel to convert the reactant mixture to a product comprising hydrogen peroxide;

transferring heat from the process microchannel to a heat exchanger; and

removing the product from the process microchannel.

2. The process of claim 1 wherein the staged addition feed stream flows through a staged addition microchannel, the staged addition microchannel being adjacent to the process microchannel, the process microchannel having an entrance for the process feed stream, the staged addition feed stream entering the process microchannel downstream of the entrance.

3. The process of claim 1 wherein the catalyst is positioned within a reaction zone in the process microchannel, the staged addition feed stream contacting the process feed stream in the reaction zone.

4. The process of claim 1 wherein the catalyst is positioned within a reaction zone in the process microchannel, the staged addition feed stream contacting the process feed stream in a mixing zone in the process microchannel upstream from the reaction zone.

5. The process of claim 1 wherein the catalyst is positioned within a reaction zone in the process microchannel, part of the staged addition feed stream contacting the process feed stream in the reaction zone, and part of the staged addition feed stream contacting the process feed stream in a mixing zone upstream from the reaction zone.

6. The process of claim 1 wherein the process microchannel has an internal dimension of width or height of up to about 10 mm.

5 7. The process of claim 1 wherein the process microchannel is made of a material comprising: steel; monel; inconel; aluminum; titanium; nickel; copper; brass; an alloy of any of the foregoing metals; a polymer; ceramics; glass; a composite comprising a polymer and fiberglass; quartz; silicon; or a combination of two or more thereof.

10 8. The process of claim 1 wherein the heat exchanger comprises a heat exchange channel adjacent to the process microchannel.

15 9. The process of claim 8 wherein the heat exchange channel comprises a microchannel.

10 10. The process of claim 9 wherein the heat exchange microchannel has an internal dimension of width or height of up to about 10 mm.

20 11. The process of claim 8 wherein the heat exchange channel is made of a material comprising: steel; monel; inconel; aluminum; titanium; nickel; copper; brass; an alloy of any of the foregoing metals; a polymer; ceramics; glass; a composite comprising polymer and fiberglass; quartz; silicon; or a combination of two or more thereof.

25 12. The process of claim 1 wherein the process microchannel is in a microchannel reactor, the microchannel reactor having an entrance and an exit, the product exiting the microchannel reactor through the exit, the product containing unreacted O<sub>2</sub> and/or H<sub>2</sub> intermixed with the hydrogen peroxide, at least part of the unreacted O<sub>2</sub> and/or H<sub>2</sub> being recycled to the entrance to the microchannel reactor.

30 13. The process of claim 1 wherein the temperature of the process feed stream entering the process microchannel is within about 200°C of the temperature of the product exiting the process microchannel.

14. The process of claim 1 wherein the total mole ratio of  $H_2$  to  $O_2$  in the process feed stream and in the staged addition feed stream entering the process microchannel is in the range of about 0.1 to about 10.

5            15. The process of claim 1 wherein the process feed stream comprises  $O_2$  and further comprises one or more of water, methane, carbon monoxide, carbon dioxide or nitrogen.

10           16. The process of claim 1 wherein the process feed stream comprises  $H_2$  and further comprises one or more of water, methane, carbon monoxide, carbon dioxide or nitrogen.

15           17. The process of claim 1 wherein the staged addition feed stream comprises  $O_2$  and further comprises one or more of water, methane, carbon monoxide, carbon dioxide or nitrogen.

20           18. The process of claim 1 wherein the staged addition feed stream comprises  $H_2$  and further comprises one or more of water, methane, carbon monoxide, carbon dioxide or nitrogen.

             19. The process of claim 8 wherein the process microchannel exchanges heat with a heat exchange fluid flowing through the heat exchange channel.

25           20. The process of claim 19 wherein the heat exchange fluid undergoes a phase change as it flows through the heat exchange channel.

30           21. The process of claim 20 wherein the heat flux between the heat exchange channel and the process microchannel is in the range of about 1 to about 50 watts per square centimeter of surface area of the process microchannel.

             22. The process of claim 21 wherein the heat exchange fluid comprises water.

23. The process of claim 21 wherein the heat exchange channel has a length of up to about 1.5 meters.

24. The process of claim 21 wherein the heat exchange channel has a length of up to about 1 meter.

25. The process of claim 20 wherein up to about 50% of the heat exchange fluid is boiling.

26. The process of claim 8 wherein an endothermic process is conducted in the heat exchange channel.

27. The process of claim 26 wherein the endothermic process comprises a steam reforming reaction or a dehydrogenation reaction.

28. The process of claim 8 wherein a process fluid flows through the process microchannel in a first direction, and a heat exchange fluid flows through the heat exchange channel in a second direction, the second direction being cross current relative to the first direction.

29. The process of claim 8 wherein a process fluid flows through the process microchannel in a first direction, and a heat exchange fluid flows through the heat exchange channel in a second direction, the second direction being cocurrent relative to the first direction.

30. The process of claim 8 wherein a process fluid flows through the process microchannel in a first direction, and a heat exchange fluid flows through the heat exchange channel in a second direction, the second direction being counter current relative to the first direction.

31. The process of claim 8 wherein a heat exchange fluid flows through the heat exchange channel, the heat exchange fluid comprising air, steam, liquid

water, carbon dioxide, gaseous nitrogen, liquid nitrogen, a gaseous hydrocarbon or a liquid hydrocarbon.

5           32.    The process of claim 1 wherein the catalyst comprises a metal from Group VIII of the Periodic Table, or an oxide thereof, or a mixture of two or more thereof.

          33.    The process of claim 1 wherein the catalyst comprises Fe, Co, Ni, Ru, Rh, Pd, Os, Ir, Pt, or an oxide thereof, or a combination of two or more thereof.

10           34.    The process of claim 1 wherein the catalyst comprises Pd, Pt, or an oxide thereof, or a mixture of two or more thereof.

          35.    The process of claim 1 wherein the catalyst comprises a support  
15    selected from ceramic, alumina, zirconia, silica, aluminum fluoride, bentonite, ceria, zinc oxide, silica-alumina, silicon carbide, refractory oxide, molecular sieves, diatomaceous earth, or a combination of two or more thereof.

          36.    The process of claim 1 wherein the catalyst comprises Pd or an oxide  
20    thereof supported on a ceramic support.

          37.    The process of claim 1 wherein the catalyst is in the form of particulate solids.

25           38.    The process of claim 1 wherein the catalyst is washcoated on interior walls of the process microchannel, grown on interior walls of the process microchannel from solution, or coated in situ on a fin structure.

          39.    The process of claim 1 wherein the catalyst comprises a support, an  
30    optional buffer layer overlying the support, an interfacial layer overlying the optional buffer layer or the support, and a catalyst material dispersed or deposited on the interfacial layer.

40. The process of claim 1 wherein the catalyst is supported by a support, the support being made of a material comprising silica gel, foamed copper, sintered stainless steel fiber, steel wool, alumina, poly(methyl methacrylate), polysulfonate, poly(tetrafluoroethylene), iron, nickel sponge, nylon, polyvinylidene difluoride, polypropylene, polyethylene, polyethylene ethylketone, polyvinyl alcohol, polyvinyl acetate, polyacrylate, polymethylmethacrylate, polystyrene, polyphenylene sulfide, polysulfone, polybutylene, or a combination of two or more thereof.

41. The process of claim 1 wherein the catalyst is supported on a support, the support being made of a heat conducting material.

42. The process of claim 1 wherein the catalyst is supported on a support made of a material comprising an alloy comprising Ni, Cr and Fe, or an alloy comprising Fe, Cr, Al and Y.

43. The process of claim 1 wherein the catalyst is supported on a support having a flow-by configuration, a flow-through configuration, a honeycomb structure or a serpentine configuration.

44. The process of claim 1 wherein the catalyst is supported on a support having the configuration of a foam, felt, wad, fin, or a combination of two or more thereof.

45. The process of claim 1 wherein the catalyst is supported on a support structure having a flow-by configuration with an adjacent gap, a foam configuration with an adjacent gap, a fin structure with gaps, a washcoat on a substrate, or a gauze configuration with a gap for flow.

46. The process of claim 1 wherein the catalyst is supported on a support structure in the form of a fin assembly comprising at least one fin

47. The process of claim 46 wherein the fin assembly comprises a plurality of parallel spaced fins.

48. The process of claim 46 wherein the fin has an exterior surface and a porous material overlies at least part of the exterior surface of the fin, the catalyst being supported by the porous material.

5 49. The process of claim 46 wherein the porous material comprises a coating, fibers, foam or felt.

10 50. The process of claim 46 wherein the fin has an exterior surface and a plurality fibers or protrusions extend from at least part of the exterior surface of the fin, the catalyst being supported by the protrusions.

15 51. The process of claim 46 wherein the fin has an exterior surface and the catalyst is: washcoated on at least part of the exterior surface of the fin; grown on at least part of the exterior surface of the fin from solution; or deposited on at least part of the exterior surface of the fin using vapor deposition.

20 52. The process of claim 46 wherein the fin assembly comprises a plurality of parallel spaced fins, at least one of the fins having a length that is different than the length of the other fins.

25 53. The process of claim 46 wherein the fin assembly comprises a plurality of parallel spaced fins, at least one of the fins having a height that is different than the height of the other fins.

30 54. The process of claim 46 wherein the fin has a cross section having the shape of a square, a rectangle, or a trapezoid.

55. The process of claim 46 wherein the fin is made of a material comprising: steel; aluminum; titanium; iron; nickel; platinum; rhodium; copper; chromium; brass; an alloy of any of the foregoing metals; a polymer; ceramics; glass; a composite comprising polymer and fiberglass; quartz; silicon; or a combination of two or more thereof.

56. The process of claim 46 wherein the fin is made of an alloy comprising Ni, Cr and Fe, or an alloy comprising Fe, Cr, Al and Y.

5 57. The process of claim 46 wherein the fin is made of an  $\text{Al}_2\text{O}_3$  forming material or a  $\text{Cr}_2\text{O}_3$  forming material.

10 58. The process of claim 1 wherein the catalyst is positioned within a reaction zone in the process microchannel, the reaction zone being characterized by a bulk flow path comprising about 5% to about 95% of the cross section of the process microchannel.

15 59. The process of claim 1 wherein the contact time for the process feed stream, staged addition feed stream and product with the catalyst is up to about 500 milliseconds.

60. The process of claim 1 wherein the temperature within the process microchannel is in the range of about  $50^\circ\text{C}$  to about  $400^\circ\text{C}$ .

20 61. The process of claim 1 wherein the pressure within the process microchannel is up to about 100 atmospheres.

25 62. The process of claim 1 wherein the space velocity for the flow of process feed stream, staged addition feed stream and product through the process microchannel is at least about  $10000 \text{ hr}^{-1}$ .

63. The process of claim 1 wherein the pressure drop for the flow of process feed stream, staged addition feed stream and product through the process microchannel is up to about 100 atmospheres per meter of length of the process microchannel.

30 64. The process of claim 8 wherein a heat exchange fluid flows through the heat exchange channel, the pressure drop for the heat exchange fluid flowing

through the heat exchange channel being up to about 100 atmospheres per meter of length of the heat exchange channel.

5           65.    The process of claim 1 wherein the conversion of O<sub>2</sub> is about 10% or higher per cycle.

          66.    The process of claim 1 wherein the conversion of H<sub>2</sub> is about 10% or higher per cycle.

10           67.    The process of claim 1 wherein the yield of hydrogen peroxide is about 10% or higher per cycle.

          68.    The process of claim 1 wherein the product further comprises water, the concentration of hydrogen peroxide in the product being from about 1 to about 15   70% by weight.

          69.    The process of claim 1 wherein subsequent to removing the product from the process microchannel a regenerating fluid flows through the process microchannel in contact with the catalyst, the residence time for the regenerating 20   fluid in the process microchannel being from about 0.001 to about 10 seconds.

          70.    A process for making hydrogen peroxide, comprising:  
                flowing a process feed stream and a staged addition feed stream in a process microchannel in contact with each other to form a reactant mixture 25   comprising O<sub>2</sub> and H<sub>2</sub>, and contacting a catalyst with the reactant mixture in the process microchannel to convert the reactant mixture to a product comprising hydrogen peroxide; the process microchannel having an internal height or width in the range of about 0.2 to about 10 mm; the catalyst being contained within a reaction zone in the process microchannel; the staged addition feed stream and the 30   process feed stream contacting each other in a mixing zone in the process microchannel upstream from the reaction zone;  
                transferring heat from the process microchannel to an adjacent heat exchange microchannel; and

removing the product from the process microchannel.